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Hydrogen-Oxygen for a Navy Satellite

The Navy's Bureau of Aeronautics became interested in liquid hydrogen as a rocket fuel in the second half of 1945 in connection with its early satellite proposals. Unlike the Wright Field contract with Ohio State University, which was research-oriented with no specific application in mind, the Navy interest was, from first to last, linked directly to its proposal to use a single-stage rocket to boost a satellite into orbit. For this reason, the effort is best viewed within the broader context of the Navy's early interest in missiles and satellites.

Origins of Navy Interest in Satellites and Hydrogen

Considering the Navy's involvement in solid rocket research and development during the war, the rising interest in jet propulsion as German developments became known, the Navy's sponsorship of OSRD's Jet Propelled Missiles Panel, and the Lemmon report on jet propulsion fuels (p. 4), the interest in hydrogen would appear to be an evolutionary step. In fact, these prior events had little influence. The proposal to use liquid hydrogen to place a satellite into orbit with a single-stage-to-orbit rocket came from Comdr. Harvey Hall, a Navy physicist who had educated himself quickly in jet propulsion, had not heard of the Wright Field contract with Ohio State University on liquid hydrogen (p. 18), and had not read the Lemmon report. Neither was he acquainted with the proposals of Tsiolkovskiy, Goddard, or Oberth to use hydrogen in rockets (appendix A-2); but like Tsiolkovskiy, he had gone to chemistry textbooks in search of the most energetic fuel. Not surprisingly, Hall found and selected liquid hydrogen, and in his quest for more information on its use in rockets, he met Robert Gordon of the Aerojet Engineering Corporation, who also had gone to his textbooks and was thinking about hydrogen at about the same time.[1]

The train of events that led to the Navy's interest in satellites and the use of liquid hydrogen as a fuel in the booster rocket was triggered by information brought to the Bureau of Aeronautics in July 1945 by a young Marine officer, Lt. Abraham Hyatt. The Bureau of Aeronautics was aware of German developments in jet propulsion and rockets from intelligence reports during the war. Hyatt had been part of a technical intelligence team in Europe following closely in the wake of the advancing armies early in 1945 to interrogate German scientists and technicians and gather documents. Among the Germans interrogated in May 1945 were Wernher von Braun and his associates who had developed the V-2 at Peenemünde. Among the documents Hyatt brought to the Bureau of Aeronautics in July 1945 was a summary by von Braun of liquid propellant rocket developments in Germany and his view of future prospects. Von Braun listed five future possibilities: (1) rocket-propelled transports for intercontinental travel; (2) multi-stage, piloted rockets orbiting the earth; (3) a large space station orbiting the earth; (4) a large orbiting mirror to concentrate solar energy and beam it to the earth for various purposes, including weather control;* (5) travel to other planets but "first of all to the moon," possibly by harnessing atomic energy. Von Braun saw the rocket as having the same impact on future scientific and military activities as the airplane.[2]

Among those in the Bureau of Aeronautics who were most excited over the potential of satellites were Lt. Robert Haviland and Comdr. Harvey Hall. By the first part of August, Haviland had written an internal memorandum proposing that the Navy initiate a program leading to a manned space station. He developed the Tsiolkovskiy equation† relating vehicle velocity to exhaust gas velocity and mass ratio, but referred only to available fuels, with no mention of hydrogen. A British report of March 1945 on the mass of various components of the V-2 was used by Haviland to calculate the terminal velocity of a two-stage rocket based on these masses. The result was disappointing; the second stage velocity was too low to achieve orbit. To get out of this dilemma, Haviland drew on a 1934 publication of E. Sänger to assume that an exhaust gas velocity of 3500 meters per second was achievable with gasoline and oxygen.‡ This is highly optimistic even at altitude: the V-2 exhaust gas velocity, using alcohol-oxygen, was only about 2/3 that value. However, his conservative mass and optimistic rocket performance assumptions led him to the correct conclusion that a satellite could be launched with a two-stage rocket booster using gasoline-oxygen. He wisely included a recommendation that more research be undertaken to secure a high energy fuel. As a further assurance of success, he suggested that the launch be made from a mountain top, to gain altitude, and in the direction of the rotation of the earth, to gain rotational velocity.[3]

In spite of his excitement over satellites, Hall took a slower and more deliberate course than Haviland. For one thing, he was not well acquainted with jet propulsion, but having a doctorate in physics, he went to basic concepts to work out the flight and energy relationships for himself. In the process, he also obtained the Tsiolkovskiy

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* The same month that Hyatt brought von Braun's predictions to the Bureau of Aeronautics, *Life* published an article on the German plans for a large orbiting mirror which was also a manned satellite. The article stated that the Germans had planned to use the mirror to focus the sun's rays into a beam to scorch the earth. *Life* 19 (23 July 1945): 78-80.

† The Tsiolkovskiy equation is $V=V_r \ln(M_o/M_e)$ where V is the maximum velocity of the rocket in gravity-free, drag-free flight; V_r is the rocket exhaust velocity; ln is the natural logarithm; M_o is the initial, full, or gross mass of the rocket; and M_e is the final or empty mass of the rocket. The two masses differ by the amount of propellant expended. More details are given in appendix A-2.

Haviland used Willy Ley, *Rockets, the Future of Travel beyond the Stratosphere*, 1944, for tabulated values in the Tsiolkovskiy equation.

‡The NACA translated and published the Sánger paper in 1942 as Technical Memorandum 1012.

equation. He then began to explore the extremes of its two variables—exhaust gas velocity, determined by the energy of the reactants and expansion through the nozzle; and mass ratio, determined by the structure. He could have obtained excellent data on exhaust gas velocities of various propellants from the Lemmon report which had been issued in May, but it had not come to his attention. Instead, he simply went to his chemistry textbooks in search of the most energetic fuel he could find to use as a yardstick in comparing the performance of various fuels. There he found the hydrogen-oxygen combination, whose heat of combustion had been measured numerous times since Lavoisier and Laplace first measured it in 1783. Hall was totally unaware that he was repeating the same steps Tsiolkovskiy had taken almost a half century earlier (appendix A-2).

In considering the ratio of initial to final mass, Hall thought of very light structures, somewhat analogous to Oberth's, and his structural design was as optimistic as Haviland's was conservative. Hall's calculations led him to believe that, using liquid hydrogen and oxygen and very light structures, he could put a payload in orbit with a single-stage vehicle, eliminating the complications of multiple staging.

Hall wanted to discuss his calculations with rocket experts, so he visited the Jet Propulsion Laboratory (JPL) of the California Institute of Technology where he met with Martin Summerfield, Frank Malina, and Homer Joe Stewart.* Encouraged by his visit, Hall went on to the Aerojet Engineering Corporation to talk about rocket propellant experiments.

Aerojet Propellant Research, 1944–1945

At the end of 1944, the Aerojet research group, headed by Fritz Zwicky, noted astrophysicist at the California Institute of Technology, had completed a Navy contract to investigate high-energy solid and liquid propellants. The results led the investigators to monopropellants; they were enthusiastic over the possibilities of using nitromethane, which has a theoretical exhaust velocity of 2200 meters per second. Zwicky was aware of other Navy-sponsored work on boron hydrides that had potential exhaust velocities of 2800 to 3100 meters per second—considerably higher than nitromethane but also much further from practical utilization.[4] At the time of Hall's visit, Aerojet was in the second phase of investigating nitromethane—determination of its experimental performance and handling characteristics. David A. Young and his new assistant, Robert Gordon, were in charge of the work, and Hall asked them about the combustion properties of hydrogen and oxygen.

Gordon had worked on aircraft engines at the power plant laboratory at Wright Field for several years and later was a navigator with the Eighth Air Force in Europe. There he had acquired a first-hand awareness of German competence in jet propulsion.

*Rocket research began at the Guggenheim Aeronautical Laboratory of the California Institute of Technology (GALCIT) in 1936 and was known as the GALCIT Rocket Project. GALCIT became the undisputed leader in rocket research during the 1940s. In 1944 the project was reorganized and named the Jet Propulsion Laboratory, GALCIT; it is now called the Jet Propulsion Laboratory of the California Institute of Technology or simply JPL. R. Cargill Hall, "GALCIT-JPL Developments, 1926–50, a Chronology," 8 Sept. 1967, NASA History Office.

He took part in bombing Peenemünde, observed the launching of a V-2, and was attacked by ME-163s—the first rocket-powered aircraft. Gordon joined Aerojet in July 1945 and during his orientation, Young introduced him to the fundamentals of rocket theory. Gordon then began calculating theoretical rocket performance of various propellant combinations using the heat of formation of exhaust products. This lead to the consideration of the simplest and most energetic reaction—hydrogen and oxygen—and he asked Young to let him try hydrogen-oxygen in a rocket experiment.[5]

Aerojet's First Series of Experiments, 1945–1946

Hall's visit to Aerojet was fortunate in its timing. He believed that he brought a new idea to Young and Gordon because none of Aerojet's previous work or proposals on propellants mentioned liquid hydrogen as a fuel. To Gordon, however, here was his boss's boss—the Navy—voicing ideas similar to his own and he was eager to get started. After Hall returned to Washington, Aerojet was authorized to experiment with hydrogen and oxygen as part of their nitromethane contract. In less than a month, Young and Gordon operated the first recorded run of a hydrogen-oxygen rocket in the U.S. on 15 October 1945.* The run ended after 15 seconds when the uncooled thrust chamber burned out, but not before a thrust of 200 newtons (45 lb) and a chamber pressure of 25.5 atmospheres were recorded. From these, the experimenters estimated the exhaust velocity to be 2600 meters per second.[6] They were undaunted by the burnout and began preparations to use a water-cooled thrust chamber. In the next test, they obtained a lower exhaust velocity, and in spite of water cooling, the chamber showed signs of overheating.†

From the first test in October until the end of the first phase of the work in June 1946, about 50 rocket runs were made at thrusts of 445 and 1780 newtons (100 and 400 lb) and chamber pressures of 20.4 and 34 atmospheres. The experimenters found it relatively easy to achieve high performance (3050 meters per second). Much of the work was concentrated on cooling and several methods were tried. One was a porous chamber through which water was forced as a form of transpiration or "sweat" cooling. Another was gaseous hydrogen flowing through the porous combustion chamber. The main method, however, remained water cooling.

As had other experimenters since the eighteenth century, the Aerojet research team found that hydrogen and oxygen ignite very readily and burn over a wide range of mixture ratios. Rapid burning meant that the combustion chamber could be small, and this led Young to his idea of the ultimate small thrust chamber—the "flared tube."

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*Richard B. Canright operated a gaseous hydrogen-oxygen rocket at JPL about 1943, but no reports on this work have been found. The first JPL laboratory was referred to as the "Gashouse" and apparently Canright used gaseous hydrogen and oxygen, mainly for their convenience and availability. Howard S. Seifert, "Twenty-Five Years of Rocket Development," *Jet Propulsion* 25 (Nov. 1955):595; telephone interview with Howard Seifert, 22 Aug. 1973; Seifert to Sloop, 29 Nov. 1973; telephone interview with Richard B. Canright, 21 Aug. 1973; interview with Richard B. Canright, Camp Hill, PA, 7 Mar. 1974. The Germans operated a hydrogen-oxygen rocket during 1937–1940 (appendix A-3).

†Average heat transfer rate was 5.7 $J/s{\cdot}m^2$; this value and the relatively low exhaust velocity are approximately the same as Ohio State obtained later at the stoichiometric mixture (p. 24, n.).

Essentially it was a straight wall tube for the combustion chamber with a flare for the expansion portion of the nozzle, as shown at the top of figure 8. Young experimented to find the minimum size tube chamber and soon became confident that he could use from 1/10 to 1/20 the volume normally used for rocket thrust chambers. This was a great step forward, for a tiny combustion chamber meant less mass for the vehicle and less surface area to cool—both big advantages. He became a missionary for the idea and set forth to sell the Navy an expanded program.

The Hall Committee

Haviland's August memorandum proposing a manned space station (p. 32) was convincing to his supervisor, Comdr. J. A. Chambers, head of a special weapons section, who saw among its advantages the possibility of a worldwide navigation and communication system on high frequencies—free from horizon limitations and sky-wave errors. He endorsed it and passed it up the line. It also received support from Capt. Lloyd V. Berkner, head of the electronics materiel branch. During this time, Hall was arguing his case for the single-stage rocket, and he must have been persuasive because on 3 October 1945, Capt. R. S. Hatcher, deputy director of engineering in the Bureau of Aeronautics, established the Committee for Evaluating the Feasibility of Space Rocketry. Its purpose was "to investigate the presently available materials and techniques and to arrive at some estimate of the possibility of attaining a velocity of liberation from one stage of operation." Hall was made chairman and the first meeting was held five days later.* Both Haviland and Hall explained their ideas, and it was revealed that detailed calculations for an earth satellite were under way in another branch of the Bureau of Aeronautics.[7]

The second meeting took place on 15 October 1945, and the subject was experimental data on some fuels and theoretical estimates on others. Lt. Comdr. F. A. Parker presented experimental data on only two propellant combinations: mixed nitric and sulfuric acid with methyl-ethyl-aniline, and alcohol with liquid oxygen. He gave their exhaust velocities at sea level as 1950 and 2300 meters per second, respectively. He thought that any hydrocarbon-oxygen system would likely have an upper limit near that of the alcohol-oxygen value. Parker estimated that increasing the combustion pressure to practical limits would increase exhaust velocity about 15 percent. A greater increase would be possible by increasing the area ratio of the exhaust nozzle. The upper limit on this appeared to be an increase in velocity of about 40 percent over sea level values. The theoretical performance of hydrogen and oxygen was given as 3000 meters per second at sea level and 4300 at altitude. The performance of diborane and oxygen was unknown, but was estimated (optimistically) to be about the same as for hydrogen and oxygen.

The Hall Committee concluded that a single-stage rocket for boosting a satellite to orbit would need an exhaust velocity on the order of 4300 meters per second and recommended that the performance of both hydrogen and diborane be investigated.

*Other members: Comdr. C. D. Case, Lt. (jg) K. W. Max, Lt. R. P. Haviland, Lt. Comdr. F. A. Parker, Lt. L. A. Hansen, Comdr. O. E. Lancaster, and J. R. Moore.

theoretically and experimentally.[8] The same day, Aerojet made their first experimental rocket test with hydrogen and oxygen. The exhaust gas velocity during the run was estimated at 2600 meters per second, which meant that 3600 would be attainable at altitude with proper design. No one had tried diborane, but Hall was attracted to it as an alternate to hydrogen. At the next meeting, on 22 October 1945, he discussed diborane and estimated that it could produce an exhaust velocity of 5500 meters per second, a value far greater than that for hydrogen-oxygen.[9] Diborane therefore appeared to be the dream fuel, but Parker pointed out that boron oxides, formed during combustion of diborane and oxygen, might solidify when expanded to the lower temperatures in the nozzle, and this would lower performance.* L. A. Hansen raised the problem of dissociation, where energy is absorbed in breaking molecules apart, which would further reduce the exhaust velocity. In spite of these cautions, the committee accepted the 5500 meters per second theoretical value for diborane-oxygen and estimated that actual performance would probably be close to the desired 4300. Hall recommended that: (1) an experimental program be initiated leading to a satellite orbiting the earth at an altitude of 1850 kilometers; (2) engineering layouts be made on the basis of an exhaust velocity of 4300 meters per second and a mass ratio of 10, and an empty mass of at least 4500 kilograms; (3) the vacuum performance of the most promising fuels having estimated exhaust velocities of 4300 meters per second be tested; and (4) diborane and similar compounds be studied. With this proposal, Hall—the original proponent of hydrogen-oxygen—was now referring to that combination only indirectly in terms of performance and was urging the study of diborane as a fuel. The committee agreed with Hall's proposal for an engineering design layout with his guidelines, but made no reference to diborane.

By the fourth meeting, on 29 October, the committee amended the minutes of the previous meeting to agree with Hall's higher estimate for the performance of diborane. Both Lancaster and Haviland, however, had analyzed boosters, and they continued to prefer hydrogen and oxygen. The two analysts differed in their mass assumptions. Lancaster found an initial-to-final mass ratio of 10 impractical, but Haviland did not. The committee found both sufficiently close to the desired goal to be promising and recommended that a more detailed study be made.[10] This was carried out by Lt. Comdr. Otis E. Lancaster and J. R. Moore.

In November 1945, Lancaster and Moore reported their study: "Investigation on the Possibility of Establishing a Space Ship in Orbit above the Surface of the Earth." Using the basic energy relationships and a simplified formula for estimating structural weight, comparisons were made of the minimum mass ratio needed for rockets to orbit at various altitudes with the mass ratios attainable with several propellant combinations. Liquid hydrogen–oxygen was considered the best on the assumptions

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*Parker was right. In 1948, at the NACA Conference on Fuels, Flight Propulsion Research Laboratory, Cleveland, the author, P. M. Ordin, and V. N. Huff reported results from rocket experiments in which boron oxides were deposited on the nozzle, verifying Parker's speculation. In the 1950s the Navy and Air Force mounted a major effort to use boron hydrides in turbojet engines and failed, largely because boron oxides clogged the turbine blades. *Hearings on Boron High Energy Fuels before the Committee on Science and Astronautics*, U.S. House of Representatives, 26–27 Aug. and 1 Sept. 1959.

of a jet velocity of 4300 meters per second in a vacuum, which was realistic. The structural formula, however, made mass ratio results very pessimistic. Lancaster and Moore concluded that an initial-to-final mass ratio of from 10.9 to 12.1 was needed to orbit at a high altitude. Since the structural mass formula indicated that for a ratio of 10, a very large rocket (one with a mass of some 2270 metric tons) would be necessary without considering payload, the authors concluded that a single stage to orbit was not feasible.* A multiple stage rocket using alcohol and oxygen, however, could orbit a satellite.[11]

The analysis was a blow to Hall's single-stage-to-orbit concept, and he proposed that JPL conduct an independent analysis.

JPL Study

The rocket experts of the Jet Propulsion Laboratory of the California Institute of Technology began their study of single-stage rockets for the Bureau of Aeronautics in December 1945 and completed it by July 1946† They wrote six reports, with the earliest appearing on 3 January 1946. The study was based on three assumptions: (1) the orbiting vehicle would be a single-stage liquid propellant rocket, (2) the propellants would be liquid hydrogen and liquid oxygen, and (3) the exhaust velocity of the rocket would be 3240 meters per second at sea level and 4320 at very high altitude. The rocket performance values were furnished by David Young of Aerojet. With these assumptions, the JPL men sought to determine the most suitable trajectory and designs for minimum initial-to-final mass ratio.

The final report, appearing in July, stated that if the single-stage rocket was launched from sea level, the initial-to-final mass ratio must be 8.70; if launched from a high mountain (4300 m), the mass ratio could be decreased slightly.[12] These results made clear to the Bureau of Aeronautics what the next steps should be: expand Aerojet's work on the experimental performance of hydrogen and oxygen and get improved weight estimates for rocket engines and vehicle structures. The latter called for the experience of an airframe manufacturer. The JPL-GALCIT study also pointed out that the mass ratio requirements for orbiting a satellite could be greatly reduced if multiple-stage rockets were used.

Apparently as a derivative of these classified military studies, Frank Malina and Martin Summerfield reported on the problem of escape from earth by rocket in August 1946, and Malina presented the results at the Sixth International Congress for Applied Mechanics at Paris in September. They made a strong case for using hydrogen-oxygen. A multistage rocket using nitric acid and aniline (a combination in use at that time) was considered too large to be practical even for a 5-kilogram payload. They concluded

*Lancaster and Moore doubted the accuracy of the structural masses they were using and recommended that a detailed structural design study be made. They also recommended intensifying the research program on rocket fuels and engines to find fuels with higher exhaust velocities and to develop larger engines.

†Participating in the study were W. Z. Chien, Lt. Comdr. E. C. Sledge, Lt. Comdr. G. G. Halverson, J. V. Charyk, and H. J. Stewart. Stewart wrote the final report.

that a multistage rocket of reasonable size using liquid hydrogen and liquid oxygen could carry a payload of 45 kilograms and was within engineering feasibility. They assumed an exhaust velocity of 3660 meters per second for hydrogen-oxygen, five stages, and a gross mass of 37600 kilograms. The authors also pointed out the advantages of using hydrogen as the working fluid with heat supplied by a nuclear reaction. Potential exhaust velocities were as high as 11400 meters per second—close to the vehicle velocity needed for escape from the earth's gravitational field.[13]

Attitudes towards Missiles and Satellites

While the advocates of satellites in the Bureau of Aeronautics were pursuing their technical studies, they were also attempting to obtain high-level support. They estimated that five to eight million dollars would be needed, but in the budget competition, they faced an uphill struggle. Ironically, their sister service, the Army Air Forces, had support at the top but little initiative at the working level. During September, the AAF's Scientific Advisory Committee, headed by Dr. Theodore von Kármán, issued the first volume of its series, *Towards New Horizons*—a bold assessment of future developments.[14]

On 12 November 1945, in his Third Report to the Secretary of War, Gen. H. H. Arnold predicted that strategic bombers would eventually be replaced by long-range ballistic missiles that would need to be launched "from true space stations, capable of operating outside the earth's atmosphere."[15]

If the Bureau of Aeronautics men were heartened by Arnold's statement, they must have been dismayed the next month at the lack of support from the top scientist in the government. In December, Vannevar Bush, Director of the Office of Scientific Research and Development, appeared before the Special Senate Committee on Atomic Energy and stated:

> There has been a great deal said about a 3000-mile [5600 km] high-angle rocket. In my opinion such a thing is impossible and will be impossible for many years.[16]

Bush was not alone. The following April, the chairman of the National Advisory Committee for Aeronautics, Jerome C. Hunsaker, echoed the same view in an address before the National Academy of Sciences:

> One is tempted to speculate about the possibilities of an improved rocket of this type [V-2]. An engineer cannot see much prospect for an improved propellant nor for much better materials of construction. It is unlikely that a ratio of starting weight to empty weight of much more than three can be obtained. It, therefore, appears that the range of 200 miles is near the maximum for the type.[17]

By the first part of 1946, the funding prospects for the satellite project were well below what its supporters in the Bureau of Aeronautics considered to be a minimum. They decided that drastic action was needed to save the project and contacted the AAF regarding a jointly supported satellite project. A meeting on satellites was held on 7 March 1946, with Hall speaking for the Bureau of Aeronautics on the proposed joint effort. The initial reaction was favorable and Hall was elated. However, his joy was shortlived; in less than a month he was called to the office of Lt. Gen. Curtis E. LeMay, the AAF deputy chief for research and development, and told that the AAF would not support the Navy proposal. LeMay did leave the door open for future discussions on earth satellites.[18] Almost coincident with the meeting on 22 March a JPL–Army Ordnance WAC rocket became the first American rocket to go beyond the earth's atmosphere. It reached an altitude of 93 kilometers.

The Air Force's Interest in Satellites

With Arnold an outspoken proponent for long-range missiles and satellites, the Air Force was not about to take a back seat to the Bureau of Aeronautics on the subject. An organization well staffed to study the potentialities of military satellites had just been formed—a "think tank" known as Project RAND.*

Soon after the meeting with Hall, LeMay instructed the Douglas Aircraft Company, RAND's parent organization, to give priority to a design study of a satellite vehicle. He wanted the basic study in three weeks "to meet a pressing requirement."[19] Douglas assigned the top manpower of its Santa Monica engineering department to this task and stopped all other RAND studies and several important Douglas design projects.

At the peak, over fifty of the best scientists and engineers of the firm were on the study—including Louis Ridenour and Francis H. Clauser, both of whom had been in the team that interrogated Wernher von Braun in 1945. The result of the study, "Preliminary Design of an Experimental World-Circling Space Ship," was hand-carried to Wright Field on 12 May 1946. Project RAND stopped further work while the Air Force evaluated the report and decided what further studies were wanted.

World Circling Spaceships

In their first quick look, the RAND group faced the same problems as the earlier investigators at the Bureau of Aeronautics and JPL. Simple physics gave the required orbital velocity and the Tsiolkovskiy equation gave the vehicle velocity without drag or pull of gravity. The major unknowns, other than those velocity losses, were the structural weights and the performance of propellant combinations. The velocity losses were not difficult to assess. The V-2 data furnished a guide for structural mass estimates as well as the actual performance of the alcohol-oxygen propellant combination. RAND considered 39 different fuel-oxidizer combinations and found that hydrogen-oxygen ranked highest (the same result as the Lemmon report, p. 4).

*Project RAND was the brainchild of Frank Collbohm, an engineer working for the Douglas Aircraft Company. In late 1945, he talked to government officials about forming a postwar scientific organization to work on problems of national security. He got plenty of expressions of interest but no action until he met General Arnold in October 1945. Arnold liked the idea and implementation began the same day. On 2 March 1946, the Douglas Aircraft Company was given a letter contract for $10 million to set up an autonomous group of engineers and scientists, Project RAND. On 12 May 1947, RAND became an independent corporation. William Leavitt, "RAND—The Air Force's Original Think Tank," *Air Force/Space Digest*, May 1967, p. 100.

Hydrogen's low density, low temperature, and wide explosive range would cause problems, but RAND decided to accept it for design studies anyway. A parallel design study used alcohol and oxygen. A satellite with a mass of 227 kilograms was selected as the payload to orbit at 556 kilometers.[20]

The RAND study gave the V-2 structural mass as 18 percent of its initial mass, estimated that 16 percent was as good as could be obtained, and used the latter for propellants not involving hydrogen. The larger tank needed for low-density hydrogen would probably increase the structural mass proportion to 25 percent.* This, of course, greatly offsets the advantages of the high exhaust velocity of the hydrogen-oxygen combination. Not surprisingly, RAND concluded that a vehicle using either hydrogen-oxygen or alcohol-oxygen could not reach orbital velocity with a single stage—a repudiation of the Navy proposal.

The RAND study found that with multistage rockets, however, orbital velocities could be reached with either hydrogen-oxygen or alcohol-oxygen, but the designs would differ considerably. The alcohol-oxygen vehicle required 4 stages with an initial mass of about 100 metric tons. A 2-stage vehicle using hydrogen-oxygen, but having a third more mass, could do the same job. A 3-stage hydrogen-oxygen rocket would reduce the initial mass to below that of the alcohol-oxygen vehicle. RAND concluded that hydrogen-oxygen should be given serious consideration in any future study. The cost of constructing and launching a satellite was estimated at $150 million over a 5-year development period.

The RAND study gave the AAF a strong position in discussing satellite proposals with the Bureau of Aeronautics. The War Department had a mechanism for coordinating similar programs between the air services—the Aeronautical Board, created during World War II. In June 1946, the board considered the satellite studies of the two services and took the neutral position that both should continue their studies independently.[21] Both the Bureau of Aeronautics and the Air Force moved to strengthen their positions.

The Air Force instructed RAND to start a 6-month study to provide a design sufficiently complete that development contracts could be negotiated for a vehicle capable of launching a satellite. For their part, the Bureau of Aeronautics contracted with North American Aviation for a 90-day study of the feasibility of their proposal, using the GALCIT structural limits as a guide. For a more detailed study of the structural aspects, the Navy also contracted with the Glenn L. Martin Company for a 12-month study, using the same guidelines as the North American contract. To supply data on rocket power plants, the Navy contracted with Aerojet for the detailed design study of a 1.33 meganewton (300000 lb thrust) engine suitable for a vehicle of 45400 kilograms initial mass. The Navy called its vehicle the High Altitude Test Vehicle, or HATV.

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*Structural mass is generally assumed to be the final mass less payload and engine; the RAND structural figures are not convertible directly into initial-to-final mass ratios.

North American Aviation Study

On 26 September 1946, North American Aviation reported the results of its study. The Navy had specified an initial mass of 45 360 kilograms with a 454 kilogram payload. From the GALCIT report series, an initial-to-final mass ratio of 9.09 was assumed (which meant a propellant mass of 40 370 kg and an engine and structural mass of 4536 kg). Aerojet was asked for an estimate of the rocket engine mass and gave a range of 1361 to 2268 kg. North American used the higher number, leaving an equal mass for the structure—comprising the tanks, supporting structure, external vanes, controls, and skin. R. G. Wilson, the principal structural analyst, found that a structure with a mass of 2903 kg—635 over the limit—was the lightest that could be designed for the propellant mass specified. This increased the initial mass of the vehicle (to 45 995 kg), and Wilson concluded that the use of a single-stage rocket to achieve orbit was not possible with the specifications given. This not being what the Navy wanted, Wilson added that if the initial mass was increased to 59 000 kg and rocket burning time to 165 seconds, the vehicle could achieve orbit with a single stage.[22]

The North American Aviation study reloaded the Navy's guns. A 59 000 kg vehicle could place 454 kg in orbit with a single-stage vehicle, whereas the Air Force with the RAND study needed from 2 to 4 stages and initial masses 1½ to 2 times greater to place half as much payload in orbit. One reason for the light North American design was pressure-stabilized tanks with a common bulkhead separating the liquid hydrogen and oxygen. Pressure-stabilized tanks are thin-walled vessels without bracing which depend upon internal pressure for rigidity in the same manner as does a balloon. The technique had been proposed by Oberth in 1923 (p. 262) and was a controversial design in the 1940s and early 1950s.

Concurrent with the North American study, RAND was proceeding with its second phase of satellite studies scheduled for completion by the end of January 1947. The RAND engineers selected vehicle mass, volume, and complexity as criteria for evaluating a number of propellant combinations. Hydrogen-oxygen was still the best on the basis of initial mass, but considering all three criteria, RAND liked hydrazine-fluorine better. The study was far from complete when the North American Aviation report came out. In the interim, James Lipp of RAND wrote a special report on the advantages of satellites. Using an estimate of $50–150 million to orbit a satellite in the 1950s, Lipp urged a quick start so that the United States could maintain superiority over possible enemies. He recommended that the AAF be given priority for a research program leading to a satellite.[23] This recommendation was strengthened a week later when Army Ordnance launched a V-2 from White Sands. The missile reached an altitude of 120 kilometers and took motion pictures of 100 000 square kilometers of the earth's surface. Lipp's arguments, however, fell on barren ground, for the country was complacent in its atomic bomb superiority—a complacency that was to last until the Russians exploded their bomb in 1949.

Fading of Satellite Proposals

The competition between the Air Force and the Navy's Bureau of Aeronautics over satellites might have grown keener had it not been overshadowed by national and international events. In the fall of 1946, President Truman's administration faced formidable problems at home and abroad. The railroad strike in August had threatened to paralyze the nation's transportation system, and Truman had countered by threatening to take over the railroads and draft its workers into the military. On the international front, the hoped-for mutual understanding with the Russians became less likely as Stalin became increasingly more hostile. With the United States facing increasing obligations abroad, preparations for the next year's budget brought decisions to restrict long-range research and development programs in favor of expenditures promising more immediate benefits. By December, such strictures had ended the prospects for satellites as a military weapon. The Air Force ordered RAND to shift emphasis from satellites to airplanes and ramjet vehicles.

During the first quarter of 1947, Project RAND wound up its first satellite study and published a final report in April. The favored configuration was a 3-stage rocket using hydrazine and oxygen, with an initial mass of 38 600 kilograms and an orbit altitude of 648 kilometers. The cost for a satellite in orbit was estimated to be $82 million.[24] If there was no immediate result, RAND's dozen reports on satellites had an important side benefit. The RAND staff had become thoroughly versed in rocket vehicles and their potential. Although the new Air Force directive emphasized air-breathing engines, RAND continued to consider the possibility of long-range rockets. In effect, this marked the beginning of the RAND-Air Force work on intercontinental ballistic missiles—the great driving force for rocket developments in the 1950s.

The Navy, however, took a different tack. The previous August, the Naval Research Laboratory had been authorized to develop a high-altitude test vehicle for scientific research. The satellite supporters in the Bureau of Aeronautics saw science as the savior of their project and began emphasizing this aspect. In November, the Bureau of Aeronautics requested the Naval Research Laboratory to study the use of satellites for scientific research and allowed the Martin and Aerojet contracts to continue.

Aerojet and Martin Design Studies

Aerojet's contract that began July 1946 called for furnishing detailed design information to the North American Aviation and Glenn L. Martin design study groups on a hydrogen-oxygen rocket engine suitable for their vehicles. The thrust of the rocket engine was specified as 1.33 meganewtons (300000 lb), the exhaust velocity 4165 meters per second, and the mass not more than 1814 kilograms. Aerojet chose a combustion pressure of 34 atmospheres and a hydrogen-to-oxygen molar mixture ratio of 3 to 1. The combustion chamber and nozzle were to be made of porous stainless steel for transpiration cooling. Young's flared tube design concept (fig. 8) was to be used. A greater unknown than the thrust chamber was the turbopump design, and Aerojet concentrated its initial effort there. By mid-October, pump characteristic curves had been determined and a pump speed of 10000 revolutions per minute selected. Although larger than any previously designed for a rocket engine, the pump would be about the size of the turbines in turbojet engines of the period and not beyond current technology.

The Aerojet design study was completed and reported by the end of March 1947—in time for use in the Martin study but too late for the North American analysis. The

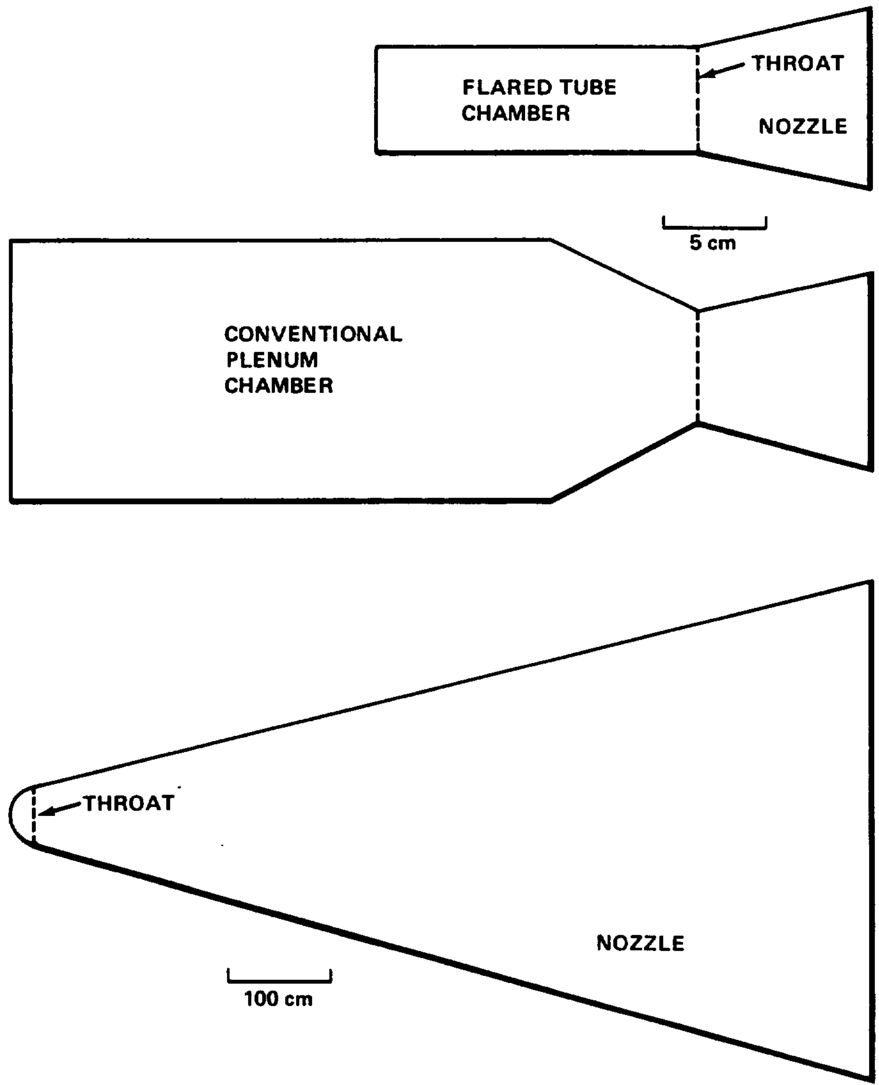

Fig. 8. Aerojet's experimental flared-tube engine (top) had less than a tenth the combustion volume of a conventional plenum chamber engine (middle) of the same size throat, nozzle, and thrust (4.5 kN or 3000 lb). Below: Aerojet's application of the flared tube concept to the design of a large engine (1.3 MN or 300000 lb thrust) where the nozzle dwarfs the combustion chamber. Note difference in scales.

thrust chamber resembled a huge ice-cream cone some 7 meters long; the combustion chamber at the small end was dwarfed by the large conical nozzle (fig. 8, bottom). The inner wall, porous stainless steel, was cooled by hydrogen flowing through it into the combustion chamber. The mass of the chamber, turbopump, and assorted valves and lines added up to 1762 kilograms, comfortably within the specifications.[25]

The Glenn L. Martin Company had the same general guidelines as North American Aviation for designing a single-stage rocket to orbit a satellite, but they too found that it could not be done within these guidelines.* In striving to do so, Martin's structural designers developed a remarkably ingenious and lightweight structure using pressure-stabilized, thin-wall tanks. With initial vehicle mass only 5 percent greater than specified in the guidelines, they managed to increase the payload by 50 percent over that specified.[26]

A comparison of the North American and Martin designs is given by table 1. Martin increased the wall thickness of Aerojet's thrust chamber and used a heavier engine than Aerojet furnished. In addition to the thin-wall, pressure-stabilized tanks, the Martin design made the large thrust chamber an integral part of the aft liquid-hydrogen tank, and added four small auxiliary rockets around the nozzle exit for stability and control. The small rockets eliminated the need for external aerodynamic stabilizer fins and movable fins in the hot exhaust stream for thrust-vector control. The idea of surrounding the thrust chamber with the tankage was remarkably similar to Tsiolkovskiy's hydrogen-oxygen spaceship of 1903 (fig. 9).

Using the same basic design, Martin analyzed a family of vehicles with initial mass from 13600 to 72600 kilograms with payloads varying from 136 to 780 kilograms. With these the Bureau of Aeronautics had a range of vehicle sizes for possible development.

TABLE 1. *Comparison of Single-Stage-to-Orbit Rocket Designs*

Item	North American	Martin
Guidelines	kg	kg
Initial mass (Navy)	45360	45360
Payload (Navy)	454	454
Engine (Aerojet)	2268	1762
Results		
Initial mass	59000	47468
Propellant	52510	42484
Final mass	6490	4984
Mass ratio (initial-to-final)	9.09	9.52
Payload	454	658
Engine	2268	2044
Structure	3768	1791
Instruments for control		491

Aerojet's Second Series of Experiments, 1946–1947

In addition to the rocket engine design study, Aerojet's contract that began in July 1946 called for experiments with a gaseous hydrogen–liquid oxygen thrust chamber. The thrust was 4.5 kilonewtons (1000 lb) and the minimum exhaust velocity was specified as 2940 meters per second. Moreover, the engine was to operate continuously

*Martin used the same JPL satellite study as North American but chose an initial-to-final mass ratio of 9.52, rather than the 9.09 used by North American.

for three minutes. The chief experimenters were Robert Gordon and Herman L. Coplen, reporting to David Young. By the end of the twelve month period they had met the specified performance.

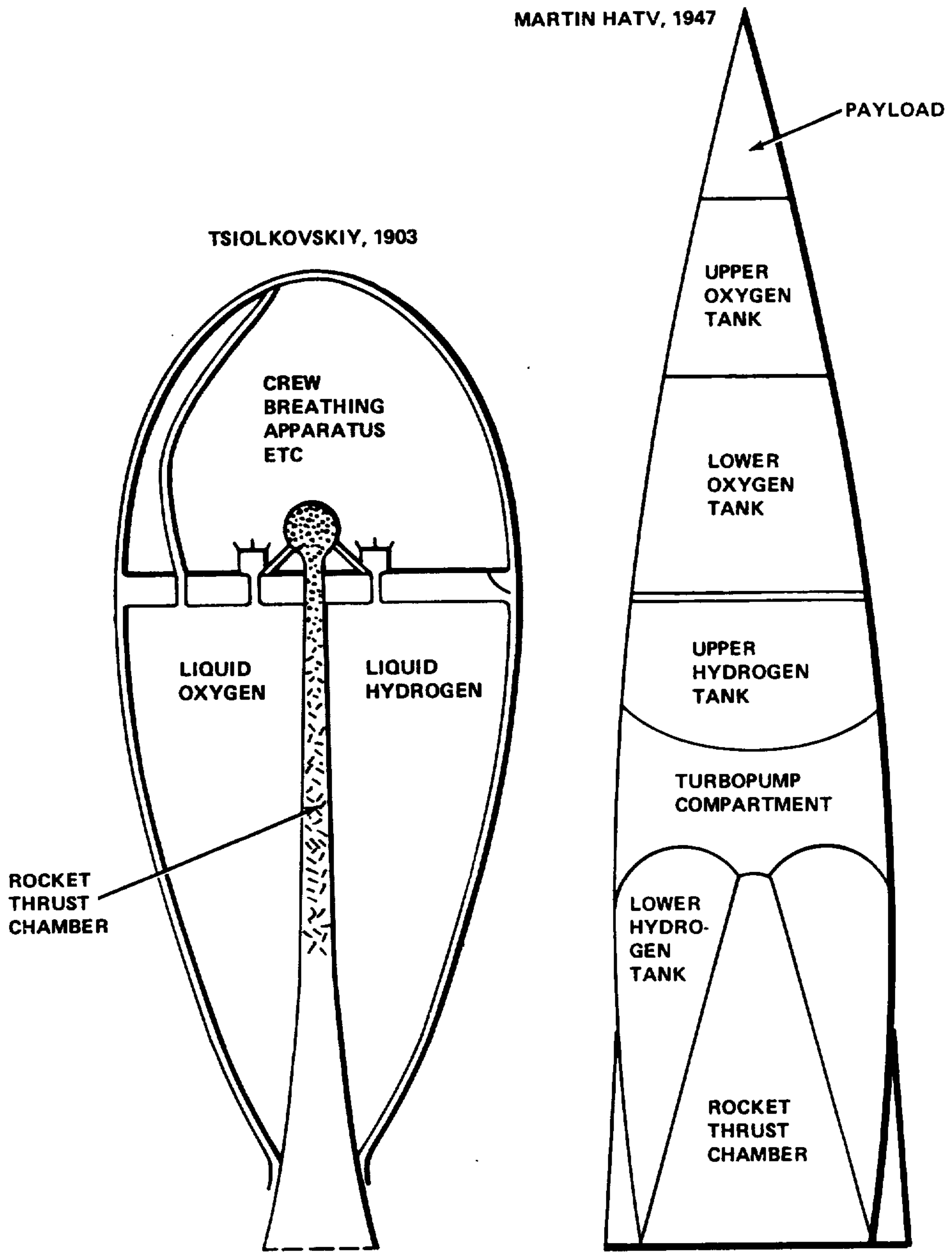

Fig. 9. Comparison of Tsiolkovskiy rocket concept (1903) and Martin HATV (1947). Note similarity of integral tanks and thrust chambers in the aft sections.

The thrust chamber had a water jacket and an inner liner of porous material through which the water seeped and evaporated on the inner surface for cooling. The shape was the flared tube design (fig. 8), having in this case a chamber diameter of 5 centimeters and overall length of 21. The gaseous hydrogen was injected through a series of holes to form a cone in the chamber, and the gaseous oxygen was injected radially inward to intercept the hydrogen cone. The combination of this injector and the flared tube design produced very high heat transfer rates—several times higher than normally experienced in rocket experiments. This led to a separate investigation of the characteristics of the flared tube by Gordon using a smaller engine independently cooled with water. Gordon found that high performance (95 percent of theoretical) could be obtained with the design, but the combustion pressure was not constant as in a conventional plenum chamber; it dropped rapidly throughout the length of the flared tube chamber.[27] The average heat transfer rates were much higher than those of a plenum chamber.*

Instead of reconsidering their basic engine design, the Aerojet men focused most of their attention on cooling. They tried a dozen different porous materials. Porous nickel made by the Amplex Division of the Chrysler Corporation proved to be the best. An attempt was made to match the water flow through the porous liner with the large variation of heat transfer rate along the combustion chamber and nozzle, but this was only partially successful. The best they could do was to use almost twice as much coolant as they had originally calculated to be necessary. This was a matter of some concern, as the water entering the combustion chamber diluted the propellant and lowered performance, for its mass had to be considered in determining thrust per unit mass flow or its equivalent, exhaust velocity. (One percent increase in water flow decreased the exhaust velocity by 0.75 percent.) To make up for the drop in performance, the combustion pressure was increased, which increased gas expansion and exhaust velocity. On 26 June 1947, four days after expiration of the contract, the performance objective was achieved on the 46th run, which lasted over three minutes.[28]

With these experiments, Young, Gordon, and Coplen were still confident that their 1.3 meganewton (300000 lb thrust) design study was sound, although they had yet to operate a rocket using liquid hydrogen and oxygen or to cool a hydrogen-oxygen rocket with hydrogen rather than water.

Switch in Emphasis from Military to Science

While the contracts for industrial research were producing satisfactory results, the Navy's change in tactics—emphasizing scientific purposes rather than purely military ones—required closer liaison with civilian scientists. This, in turn, implied a shedding of the secrecy that envelops military projects. Admiral Leslie Stevens of the Bureau of

*The average rate was 13 $J/s \cdot m^2$; in the section just before the nozzle, a peak of 29 was measured. Pressure was 20 atm at the injector end and the mixture was fuel-rich (oxidizer-to-fuel mass ratio of 5). The average heat transfer rate was about 6 times greater than Ohio State's values when the latter used a plenum chamber at about the same operating conditions and performance (fn., p. 24). Some of the difference can be attributed to the much greater gas velocities in the flared tube as well as the different types of propellant injection.

Aeronautics recommended in January 1947 that the Joint Research and Development Board remove the satellite project from the jurisdiction of the Aeronautical Board and "establish an agency for the coordination, study, evaluation, justification, and allocation of all phases of the Earth Satellite Vehicle Program. . . ."[29] The need for something like the National Aeronautics and Space Administration was envisioned a decade before it became a reality.

Stevens's recommendation meant the voluntary relinquishment of control over satellites by the Joint Research and Development Board. Not surprisingly, the recommendation was referred to the Aeronautical Board where it was studied for a couple of months with the not unanticipated conclusion that jurisdiction should remain where it had been. By then it was mid-1947 and although the reports of Martin and Aerojet were in, satellite considerations were becalmed in a sea of changing organizations.

On 26 July, President Truman signed the Armed Forces Unification Act. The Departments of War and Navy were abolished and the National Military Establishment was created, headed by the Secretary of Defense. The Army Air Forces became the Department of the Air Force, equal in status with the Departments of the Army and Navy. By the end of September, the old Joint Research and Development Board was replaced by the Research and Development Board under the same chairman, Vannevar Bush. Reorganization had little effect on the board and its subgroups, but there was much additional work to be done, especially in defining the role of the Air Force with respect to missiles. The Aeronautical Board and the subcommittee on earth satellite vehicles continued to function. In November, the Office of Naval Research asked to be designated the coordinating agency for the "High Altitude Research and Earth Satellite Program." Before the subcommittee reached a decision, the parent Research and Development Board gave responsibility for earth satellites to the Committee on Guided Missiles, which formed a Technical Evaluation Group under the chairmanship of Professor Clark Milliken of the California Institute of Technology.[30]

The Canright Report

During changes in government R&D organizations and objectives in 1947, rocket analysts were looking beyond the merits of exhaust velocity in comparing propellants and focusing on the importance of propellant density and its influence on vehicle design and performance. Not satisfied with an analysis by von Braun, Hager, and Tschinkel in 1946 that placed considerable emphasis on propellant density, Richard Canright of JPL developed a method of comparing propellants for rockets of the V-2 class and larger with propellant masses 70 to 90 percent of initial vehicle mass. Equal total impulse (thrust · time) was assumed; tank volume was adjusted to provide the necessary propellant in each case; and total vehicle mass was calculated. The vertical height attained by the rocket was the comparison criterion, which was almost the same as comparing initial masses.[31]

For large vehicles, Canright found that the exhaust velocity of propellant combinations was decidedly more important than propellant density and that emphasis on high energy propellants was justified. Although his analysis showed that hydrogen was superior to any other fuel using the same oxidizer, Canright favored hydrazine, finding it favorable under all the conditions assumed.*

Aerojet's Third Series of Experiments, 1947–1949

When the Navy renewed Aerojet's contract in mid-1947, the central task was to develop a liquid hydrogen–oxygen rocket engine suitable for a small-scale version of the earth satellite vehicle. The engine was to be in the thrust range of 9–13 kilonewtons (2000–3000 lb), have a minimum exhaust velocity of 2972 meters per second, and be capable of operating for 60 seconds. Maximum mass was specified as 34 kilograms. Propellants were to be supplied to the thrust chamber by a turbopump. Other tasks, which were concerned with drawings and operating instructions, indicated that the Navy intended to be prepared for development of a small-scale experimental vehicle. The contract also called for several analyses and a design study of a rocket engine of 37.8 kilonewtons (85000 lb thrust), apparently for the Martin minimum-sized vehicle. Although there was little reason for optimism, the Bureau of Aeronautics was keeping its options open.

The Aerojet work with hydrogen from mid-1947 to mid-1949 was the climax of five years of effort along three major lines: (1) the supplying of liquid hydrogen, (2) turbopump development, and (3) thrust chamber development.[32] These will be described separately.

Supply of Liquid Hydrogen

From the first tests in 1945 through the second series of rocket experiments in 1947, Aerojet had to use gaseous hydrogen because liquid hydrogen was not available. Starting in early 1946, Aerojet enlarged its facilities to handle gaseous hydrogen and oxygen. Gaseous hydrogen under a pressure of 136 atmospheres was available directly from a trailer of high pressure tubes with a capacity of 800 cubic meters (at atmospheric pressure) and from a stationary bank of high pressure tubes of about the same capacity. Gaseous oxygen at pressures up to 163 atmospheres was supplied from two trailers with a capacity of 560 cubic meters. The total quantity of gases from these sources allowed only a few minutes of operation—a situation conducive to continued frustrations, as the following incident illustrates. One day the test crew was ready to run the rocket and waiting impatiently for a commercial firm to deliver some needed gas. When it came, the crew quickly connected the trailer to the pipes leading to the test cell and ran the test. Meanwhile, the truck driver had gone to the office to get the delivery ticket validated. On his return he was told the trailer was empty and could be taken back. Used to leaving such trailers for a considerable time at other places, the

*On the basis of an altitude index of 100 for alcohol-oxygen and a tank pressure of 20 atm, hydrogen-oxygen was 153, 21 units higher than hydrazine-oxygen; the advantage of hydrogen increased if a lower tank pressure was assumed. In his initial calculations, Canright considered hydrazine-fluorine, which he found superior to hydrogen-oxygen. Later, however, Canright indicated that hydrogen-fluorine should give the maximum range obtainable from chemical reactions.

driver simply would not believe the crew until it was explained rather forcibly to him. He departed with the trailer, shaking his head.[33]

By early 1947, the Aerojet group was planning ahead to the next phase of hydrogen-oxygen experimentation and acutely felt the handicap of not having a supply of liquid hydrogen. Envying their former associate, Marvin Stary at Ohio State University, with his assured supply of liquid hydrogen from the Johnston liquefier, they decided to attack the problem directly. They discussed liquid hydrogen with several possible users on the West Coast and the idea blossomed into a proposed cooperative venture among several government agencies, universities, and industrial firms. Confident that they could get liquid hydrogen—and having gone to as high a thrust as was reasonable with gaseous hydrogen—the Aerojet engineers proposed to use liquid hydrogen in their third series of experiments starting in July 1947. They went even further and proposed to build a flyable rocket engine, complete with its own controls and turbine-driven pumps. They also recommended that the government build a medium-scale hydrogen liquefier on the West Coast.

Aerojet got its new contract in July 1947, but immediately faced a problem: the cooperative venture to get liquid hydrogen failed to materialize. Aerojet decided to try to interest private industry in supplying liquid hydrogen, and if that failed, to get authority and funding from the Navy to build a liquefier. The first step was to get an estimate of the amount of liquid hydrogen needed. The Jet Propulsion Laboratory agreed to participate and estimated a need for 600–900 kilograms a year. Aerojet added their needs and settled on a 3600-kilogram total requirement for two years. Three possible commercial sources were then queried. The Shell Development Corporation could not supply liquid hydrogen, but had a surplus of high-purity gaseous hydrogen for sale. The National Cylinder Gas Company believed that the sale of liquid hydrogen was neither economical nor safe and recommended liquefaction at the point of consumption. The Linde Air Products Company submitted an oral bid for $62 per kilogram at their plant in Los Angeles, but later lowered the price to $55 per kilogram for the first 1800 kilograms and $44 thereafter.

While soliciting industry, Aerojet began investigating the possibility of building a liquefier modeled after Johnston's and estimated that it would cost $100000, including the cost of the liquefier, materials, and labor for producing 3630 kilograms of liquid hydrogen. This was half the revised Linde estimate and had the added advantage of being under Aerojet control and located near the rocket test stand. Aerojet officials became enthusiastic over the prospect and set about convincing the Navy. By late September they received oral approval, which was formalized on 16 December 1947. Aerojet engaged Johnston as a design consultant; he was also to supply parts of the liquefier. Herman L. Coplen was the principal Aerojet engineer for design, construction, and operation.

Aerojet expected to have the liquefier in operation by late spring or early summer. As so often happens, the optimistic schedule fell victim to late equipment deliveries. However, the liquefier produced its first liquid hydrogen—12 liters—on 3 September 1948. The initial operation turned up the usual number of bugs; the second operation on 21–23 September produced 120 liters. Of this, 75 liters were shipped to the Jet Propulsion Laboratory for rocket tests there.

Aerojet was pleasantly surprised to find that the actual capacity of the liquefier was 30 liters per hour instead of the design value of 25. The increased capacity came from a larger hydrogen compressor; the Johnston-built heat exchangers were oversized. This led Aerojet to propose, in early 1949, the doubling of the liquefaction capacity by installing additional hydrogen compressors.

At first, the liquefier was operated intermittently. Beginning on 8 November, a two-shift operation was begun to meet the needs of the rocket test engineers, and from 27 December three shifts were employed. By the end of 1948, 7500 liters (535 kg) of liquid hydrogen had been produced, over 90 percent of it in November and December. Only about 30 percent of the hydrogen liquefied was used in test operations; the bulk was lost during storage and test delays.

In the first three months of operation, the liquefier was shut down twice, but the troubles were quickly fixed; the time lost was four days. Overall, the liquefier was highly successful and made possible the testing of pumps and thrust chambers.

By the end of March, Coplen had added two more compressors and the liquefaction rate rose to 80 liters (5.67 kilograms) per hour. But early March had brought catastrophic news to the liquid hydrogen producers. On 2 March 1949, the Bureau of Aeronautics directed Aerojet to change fuels from liquid hydrogen to anhydrous hydrazine, which is a liquid at room temperature and pressure.* The directive allowed Aerojet to continue liquid hydrogen testing until the end of June, but the irony was that the switch came just as the producers of liquid hydrogen were finally prepared to meet rocket test needs.

In its operations through June 1949, the Aerojet liquefier produced 47000 liters (3357 kilograms) of liquid hydrogen at an estimated cost of $29.72 per kilogram. The cost of commercial gaseous hydrogen and liquid nitrogen were major expenses.

Sometime after the contract ended in mid-1949, Aerojet received a government directive to dismantle and prepare the liquefier for shipment. Very few at Aerojet knew, but the liquefier was destined for reassembly on a remote Pacific isle for use in the first test of a thermonuclear device, the predecessor of the hydrogen bomb.

Turbopump Development, 1947–1949

The principal engineer for turbopump development was George Bosco. This was a new field for Aerojet, and during the second half of 1947, Bosco and his group learned about the pump work of others and made preliminary design studies. Aerojet representatives visited Ohio State University where Florant was working on hydrogen pumps, and consulted Dietrich Singelmann, a German pump expert at Wright Field.

*The author has been unable to pin down the reason for this sudden change, but it is not surprising. Hydrazine is storable and considerably easier to handle than liquid hydrogen, its performance is high, and interest in it during the 1940s and 1950s was high. For example, Canright, in his analysis of relative importance of exhaust velocity and density, preferred hydrazine to hydrogen even though hydrogen gave higher performance (pp. 47–48).

Bosco subsequently used Singelmann's data in designing Aerojet's first hydrogen pump.*

By mid-1948, Aerojet had selected centrifugal pumps for both liquid hydrogen and liquid oxygen. They obtained some German radial-vane pumps from the Navy and tested them during the second half of the year.+

By the end of 1948, Aerojet had designed, built, and tested a liquid-hydrogen pump (15 cm diameter). Initially, it used ball bearings that were run clean and dry, because the low temperature made conventional lubrication impractical. The pump was first operated at low speeds to allow its parts to cool down to operating temperature. When temperature gauges showed that liquid hydrogen had reached the pump, an attempt was made to accelerate from 5000 to 35000 revolutions per minute. The pump failed and examination of the pieces pointed to a failure of the bearing, as well as the impeller. After some testing, super-precision bearings, lubricated by oil that was atomized and directed by a stream of gaseous nitrogen, were used. On the next run, the bearings worked satisfactorily but the stresses were too great for the brazed impeller and it flew apart. A new one was made by milling from a solid block of aluminum. Time was running out, as the contract had less than six months to go. The next two runs with the new pump were a great disappointment; the instruments showed no significant flow or pressure rise. The problem was traced to the exit diffuser of the pump, which was too small and insufficiently cooled during the cool-down cycle so that it limited the flow. This was corrected by adding vent holes in the pump housing; the vents were opened during cool down and closed when the pump was cold. With this fix, two additional runs were made in March 1949 and both were successful. Flow rate and pressure were found to be in approximate agreement with theoretical predictions. The maximum pressure was 26 atmospheres and the flow was 0.25 kilogram per second.

Thrust Chamber Experiments, 1947–1949

From their previous work, Young and Gordon were confident that the flared tube configuration, with its very small combustion chamber, was the best design for the thrust chamber of 13.3 kilonewtons (3000 lb thrust). They intended to use a porous inner wall but were still undecided about the coolant. They decided to determine the relative merits of both water and liquid hydrogen as transpiration coolants. They also planned to study injection methods for liquid hydrogen. Stary was studying the same things at Ohio State University and had just made his first run using liquid hydrogen (p. 20).

From mid-1947 to mid-1948, the Aerojet men made few thrust chamber tests. None was made with liquid hydrogen, for the liquefier was not yet in operation. The major experimental work was an investigation of the performance loss at sea level in operating a nozzle designed for maximum performance at altitude.

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*The initial design provided for pumps for hydrogen, oxygen, and water (coolant), each with inlet and discharge pressures of 2.4 and 51 atm, respectively. The liquid hydrogen flow rate was 0.39 kg/s; oxygen, 2.1; and water, 0.54. An estimated 9.7 kW (130 horsepower) turbine was needed to drive the three pumps.

+ The pumps, made by the Bayerische Motoren Werke, were from the BMW 109-718 booster rocket engine used on the ME-262 aircraft.

The force produced by a nozzle from expanding exhaust gases is the result of a momentum force and two pressure forces. One of the pressure forces aids the momentum force and the other opposes it. An ideal nozzle is one that expands the exhaust gases from the pressure in the combustion chamber to the outside ambient pressure. The nozzle thereby maximizes the momentum force and the two pressure forces cancel each other. Since a rocket nozzle is a fixed design, the designer must choose a single ambient pressure for his design. If he chooses sea-level pressure, he gets less than optimum performance at altitude; if he chooses a lower pressure corresponding to some altitude, he theoretically loses performance at sea level. Since much of the operation occurs at reduced ambient pressure, the designer usually wishes to make the nozzle as large as mass and size restrictions permit. The question at Aerojet was: What penalty would result from sea-level operation of a nozzle designed for best operation at altitude? In experiments with a small rocket chamber they found, to their great joy, that the actual performance loss was much less than theoretically predicted—their nozzle designed for altitude had only a 10 percent loss at sea level.*

Aerojet was still committed to transpiration cooling but had encountered a series of new and worrisome material problems. It was difficult to obtain porous materials of uniform permeability—but worse yet, the porous structure became clogged in unpredictable and nonuniform ways. These problems began to raise doubts about using the flared tube configuration as well as transpiration cooling. When the project received new funding and directions in mid-1948, Aerojet planned to use a group of thrust chambers of various sizes and shapes, as well as a variety of injection methods. The engineers believed regenerative cooling would be possible with either oxygen or hydrogen, or both. Preparations were made to study the heat transfer properties of oxygen and hydrogen by means of an electrically heated tube. All of these activities signaled a major change in direction by Aerojet, from emphasis on their flared tube design using transpiration cooling to a conventional plenum thrust chamber with regenerative cooling. It was about this time, mid-1948, that George H. Osborn became the chief test engineer.

The first Aerojet test with liquid hydrogen and oxygen was made on 20 January 1949 with a 1780-newton (400 lb thrust) chamber. By the end of March, 10 runs had been made with disappointingly low exhaust velocities—about 2920 meters per second or 82 percent of theoretical. Of equal concern was the unsteady operation, or "chugging," which indicated unstable combustion. The injector, designed by Osborn, used a diverging cone of liquid oxygen intersecting a converging sheet of liquid hydrogen. The only good news was a low heat transfer rate, which was attributed to incomplete combustion.

In the midst of all the bad experimental results came the worst news of all. On 2 March 1949, as previously mentioned, the Bureau of Aeronautics directed Aerojet to change the fuel from liquid hydrogen to anhydrous hydrazine, but allowed the experiments with liquid hydrogen to continue for the three months remaining in the contract. No evidence has been found that Aerojet protested this change—perhaps it

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*The exhaust gases did not overexpand as much as theory implied, but separated from the nozzle walls at a shock front. The exhaust gases filled the nozzle up to a certain point and then separated from the wall and flowed as though the rest of the nozzle were not there.

was welcomed after the first series of experiments with liquid hydrogen. However, the Aerojet designers were determined to do a creditable job with liquid hydrogen in the time remaining and the record shows that they did. The key was injector design.

Osborn was designing new injectors even before all the dismal results with the spray type were in. The second design was a "showerhead" type with 115 fuel and oxidizer holes across the face and 30 fuel holes around the circumference for film cooling. The film, or layer, of fuel-rich gas next to the chamber and nozzle walls kept them cool. The design gave low performance and failed structurally on 4 April, three months before the end of the contract.

The pressure on the team to succeed must have been great. Fortunately, Osborn had designed a third injector, called a multitube concentric orifice, in March and it proved to be highly successful. Liquid hydrogen was injected through a number of thin-walled tubes surrounded by an annular flow of liquid oxygen, as illustrated by figure 10. For

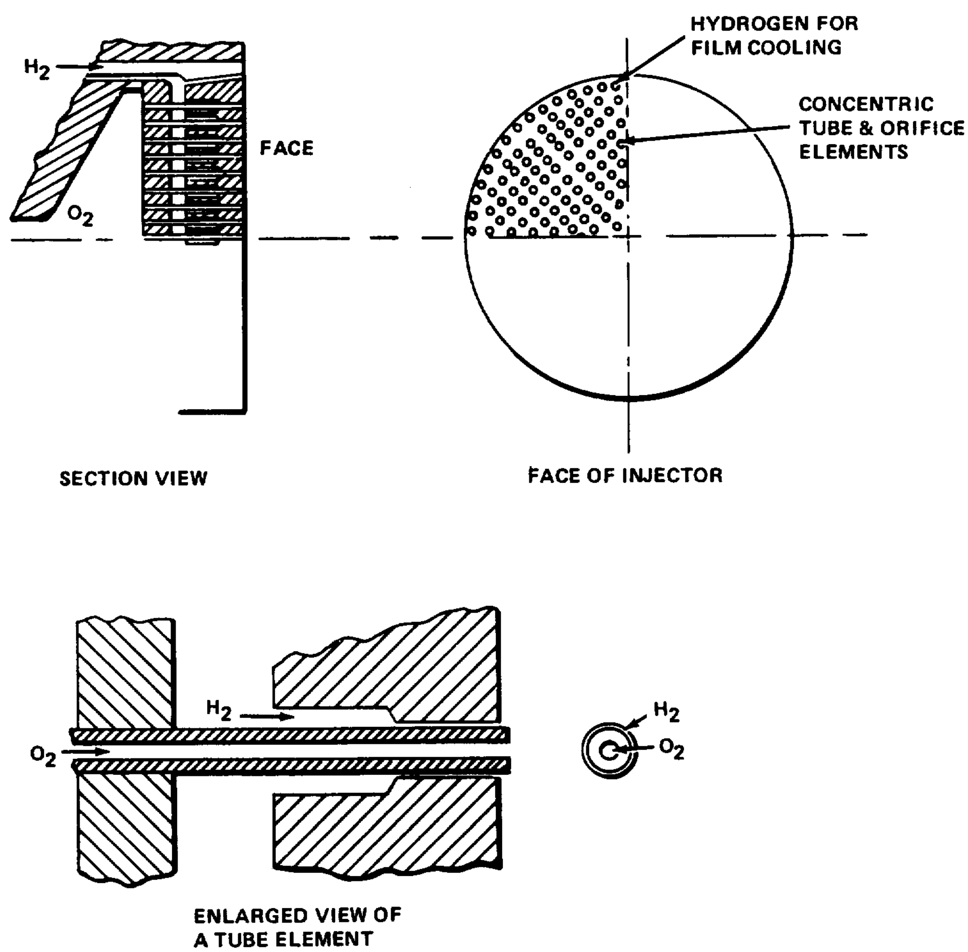

Fig. 10. Aerojet's multitube concentric orifice injector. One design had 489 concentric tube orifice elements for the 13.3-kN (3000-lb-thrust) experimental rocket.

the 1780-newton (400-lb-thrust) chamber, 61 of these "tubes within tubes" provided a very fine degree of mixing. As in the previous design, axial orifices were spaced around the circumference for hydrogen film cooling. Two runs with this injector gave an exhaust velocity of 3590 meters per second, or virtually 100 percent of theoretical. The propellants mixed so well that combustion occurred very close to the injector face and burned it. Osborn sought to correct this with design changes, but the fix did not work as well as the original design. However, he knew how he wanted to design the 13-kilonewton (3000-lb-thrust) injector. When he signed the drawing for it on 5 May, there were less than two months left to complete the work. The injector had 489 sets of circular oxygen orifices surrounding hydrogen tubes, plus 60 hydrogen orifices for a fuel-rich layer at the walls. The thrust chamber, which had been designed and fabricated earlier, was a conventional plenum chamber, water cooled, with an inner liner of copper. The copper was machined from a solid billet and its size limited the nozzle design so that it was not ideal.* Starting on 27 May three successful runs were made with this engine at pressures from 24 to 31 atmospheres. Exhaust velocities of 3380 to 3520 meters per second were obtained, approaching 95 percent of theoretical performance. On 16 June, with two weeks to go before the contract expired, they attempted to make a fourth run, but an explosion occurred in the liquid hydrogen propellant system—the second in that system. Aerojet attributed the cause to contamination of the liquid hydrogen with solid oxygen. That ended Aerojet's rocket experiments with liquid hydrogen.

In reporting the results, Osborn and Wayne D. Stinnett included experiments by Gordon on heat transfer and injectors using a smaller, water-cooled engine where the multitube, concentric injector had initially proved successful. Heat transfer rates were reported as excessive for both engines, leading the authors to conclude that additional film cooling over that used in the larger engine would be necessary. Although they had not fulfilled the objective of a self-cooled, lightweight rocket engine using liquid hydrogen-oxygen, the investigators believed that their results were highly encouraging, and no fundamental difficulties were encountered. From their rapid progress during the last four months of the contract, there is little doubt that Aerojet was on the right track in thrust chamber design and with additional work would have been able to perfect self-cooling. Concurrent with their work, Dwight I. Baker at nearby Jet Propulsion Laboratory was doing just that.

JPL Experiments with Hydrogen-Oxygen, 1948–1949

It is ironical that Young's experimental team at Aerojet, early in getting started with hydrogen-oxygen in 1945—even building a liquefier to get a supply of liquid hydrogen—was not the first to experiment with liquid hydrogen in a rocket on the West Coast. Baker, using Aerojet-furnished liquid hydrogen, beat them by four months. JPL had been interested in hydrogen-oxygen as a high-energy propellant combination since starting a study for the Bureau of Aeronautics in 1945.†

*The nozzle ratio of exit-to-throat area was 4, a ratio that theory indicates would underexpand the exhaust gases; hence the momentum force was not a maximum.

†JPL was also interested in the possible use of nuclear energy to heat hydrogen. In 1947, Walter B. Powell of JPL attempted to measure the performance of gaseous hydrogen heated electrically in a tube, but found that the thrust and flow rates were so low that accurate measurement was impractical.

When Aerojet queried JPL in 1947 for interest in using liquid hydrogen, JPL responded with an estimated need for 600 to 900 kilograms for a year of experimentation. While Aerojet's liquefier was under construction, a 100-liter dewar was built for use in transporting liquid hydrogen from the Aerojet plant to the JPL test cell. When Aerojet produced liquid hydrogen on 21 September 1948, Baker was ready and waiting. Aerojet provided 75 liters of liquid hydrogen to JPL and Baker used it in a rocket run the same day. The results were first reported in the JPL Combined Monthly Summary No. 8 for the period 20 August–20 October 1948:

> The first motor test with liquid hydrogen and liquid oxygen was made during the past period on a 100 lb thrust [445 N] motor at a nominal chamber pressure of 300 psia [20.4 atm]. . . . Three points . . . were obtained at mixture ratios [oxygen to hydrogen by weight] of 6.27, 5.46, and 4.99 . . . during a single test having a duration of 105 seconds.

With these words, JPL became the second U.S. laboratory to report rocket experiments using liquid hydrogen, a little over a year after Ohio State University's first test.

The performance obtained in the first JPL test with liquid hydrogen–oxygen was 2717 meters per second, within 15 percent of theoretical—not bad for the first attempt. The average heat transfer rate was 3.6 joules per second per square meter, much lower than measured by Aerojet but in agreement with the data from Ohio State University.

Baker was appalled at how little liquid hydrogen he was able to use in the rocket firing. Only 37 percent was burned in the rocket chamber. An estimated 21 percent was lost in cooling the transport dewar, 16 percent evaporated during transit from Azusa to Pasadena, and 26 percent was lost in cooling the propellant tank of the test rocket. If Baker had not already precooled the hydrogen containers and system with liquid nitrogen, the liquid hydrogen loss would have been much greater. This experience led JPL to use gaseous hydrogen for injector testing while reserving liquid hydrogen for heat transfer and cooling tests. They were already conducting some experiments with gaseous hydrogen which also were reported in Monthly Summary No. 8.

The gaseous hydrogen–liquid oxygen rocket experiments were conducted with a 445-newton (100-lb-thrust) chamber and the results indicated that liquid oxygen above its critical pressure cooled two-thirds of the combustion chamber, with water cooling the rest. At that time, cooling with liquid hydrogen was a big unknown, for fundamental heat transfer data on hydrogen above its critical pressure were missing. Walter B. Powell, who had built an electrically heated tube for heat transfer research, agreed to obtain the missing data. This was given first call on the next available supply of liquid hydrogen while injector testing continued with gaseous hydrogen–liquid oxygen at a higher thrust (2.2 kN or 500 lb). Baker was to use the data Powell obtained to design a regeneratively cooled thrust chamber, possibly using both liquid hydrogen and liquid oxygen as coolants.

Early in 1949, Baker succumbed to enthusiasm, confidence, or impatience and decided to go ahead with designing and testing a hydrogen-cooled thrust chamber without waiting for Powell's results. He had already calculated that liquid hydrogen had twice the heat absorbing capacity of liquid oxygen at their relative flow rates and therefore would be a better coolant. He designed a rocket engine of 445 newtons (100-lb thrust) for operation at 20 atmospheres chamber pressure. On 15 April 1949, Baker became the first person in the United States, if not the world, to operate a liquid hydrogen–liquid oxygen rocket thrust chamber that was cooled with liquid hydrogen. The test ran for 77 seconds and performance was relatively low (2630 meters per second); succeeding runs, however, established beyond any doubt that high performance and regenerative cooling with liquid hydrogen were realizable. Sixteen runs were made through 10 June 1949 over a range of hydrogen-oxygen mixture ratios, with an average running time of 69 seconds for the series. Three runs were made at a combustion pressure of 33 atmospheres and three sizes of combustion chambers were used during the series. Maximum performance was an exhaust velocity of 3420 meters per second at 33 atmospheres combustion pressure and an oxygen-to-hydrogen mass ratio of 4. Baker encountered no serious difficulties and concluded that large size, regeneratively-cooled rocket thrust chambers using liquid hydrogen–liquid oxygen were practical.[34]

Although Baker had no serious problems with burning hydrogen or cooling with it, he was still concerned over the supply of liquid hydrogen. The cost was about $45 per kilogram and he was able to burn half or less of the amount purchased, with the rest lost in transit and cooling. The hydrogen delivered was about half orthohydrogen and half parahydrogen. Baker was aware that the spontaneous conversion of orthohydrogen into parahydrogen released heat, and suggested that savings could be made if all the hydrogen were converted to parahydrogen by means of a catalyst at the liquefier. With this sensible suggestion, he anticipated developments during the 1950s.

Fading Interest in Hydrogen-Oxygen

The successful results at Ohio State University, Aerojet General Corporation, and the Jet Propulsion Laboratory with liquid hydrogen–liquid oxygen for rocket engines in the late 1940s had little effect on the higher levels of the Air Force and Navy. In late 1948, Harvey Hall and his colleagues at the Bureau of Aeronautics attempted to maintain the Navy satellite program by proposing a reconfigured HATV as a super-performance sounding rocket to obtain information on the upper atmosphere. The proposal, backed by a detailed engineering report by the Glenn L. Martin Company, was made to the NACA Subcommittee on the Upper Atmosphere and to the Geophysical Sciences Committee of the Research and Development Board. The NACA subcommittee endorsed it—but it was only moral support, for the NACA had no funds for such work. The Geophysical Sciences Committee simply listened and took no formal action. This last-ditch effort was essentially the end of the Bureau of Aeronautics struggle for a high altitude test vehicle.[35]

In 1949, the Air Force again considered satellites for military operations and directed RAND to resume satellite studies. By the end of the year, Ohio State University was the only laboratory engaged in experimental investigations of liquid hydrogen for rockets, and there William Doyle had switched emphasis from hydrogen-oxygen to hydrogen-fluorine. The Ohio State hydrogen investigations in rockets ended in 1951.